AN APPLICATION OF THE RANDOM WALK MODEL TO PROPER MOTIONS OF CORONAL BRIGHT POINTS FROM SDO DATA

I. SKOKIĆ¹, D. SUDAR², S. H. SAAR³, R. BRAJŠA² and I. POLJANČIĆ-BELJAN⁴

¹Astronomical Institute of the Czech Academy of Sciences, Fričova 298, CZ-251 65 Ondřejov, Czech Republic
²Hvar Observatory, Faculty of Geodesy, University of Zagreb, Kačićeva 26, HR–10000 Zagreb, Croatia
³Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
⁴Department of Physics, University of Rijeka, Radmile Matejčić 2, HR-51000 Rijeka, Croatia

Abstract. Atmospheric Imaging Assembly (AIA) images from the Solar Dynamics Observatory (SDO) were used to follow the motions of coronal bright points (CBPs) in the period 1 January - 19 May 2011 with a cadence of 10 minutes. This resulted in a data set of 80966 CBPs with measured lifetimes and mean velocities which were used in a random walk model to calculate the diffusion coefficient, \( D \). The results show that \( D \) has a value of \( \approx 260 \text{ km}^2 \text{ s}^{-1} \) for CBPs with lifetime below 6 hours, decreasing to \( \approx 170 \text{ km}^2 \text{ s}^{-1} \) for lifetimes above 12 hours, with a mean value of \( \approx 230 \text{ km}^2 \text{ s}^{-1} \).

Key words: Sun - coronal bright points - random walk - diffusion coefficient - SDO/AIA

1. Introduction

Coronal bright points (CBPs) are small bright structures observed in X-ray and EUV images of the Sun, associated with local magnetic reconnection above the underlying bipolar magnetic features (Golub et al., 1974; Harvey-Angle, 1993). Because of their uniform distribution across the solar disc and typical lifetime of several hours they are frequently used as tracers to study solar velocity field (e.g. Brajša et al. 2002; Vršnak et al. 2003; Kariyappa 2008; Dorotovič et al. 2014).

Diffusion of the magnetic field is an important part of theories modeling the solar dynamo. Leighton (1964) was the first to suggest that random walk model could be used to describe this diffusion process and applied it to the
motions of photospheric magnetic concentrations governed by supergranular flows. This idea was followed by Mosher (1977) who derived a value for the diffusion coefficient \( (D) \) between 200–400 km\(^2\) s\(^{-1}\). Wang et al. (1989) preformed numerical simulations of evolution of the surface magnetic field to find that convective diffusion of 600 km\(^2\) s\(^{-1}\) best fits the observations.

In a study of magnetic field concentrations from SOHO magnetograms, Hagenaar et al. (1999) found a value of 70–90 km\(^2\) s\(^{-1}\) for timescales <10 ks and 200–250 km\(^2\) s\(^{-1}\) for timescales >30 ks. More recently, Utz et al. (2010) measured a value of 350±20 km\(^2\) s\(^{-1}\) using magnetic bright points detected in G-band solar images. Abramenko et al. (2011) analyzed departures from normal diffusion and found a super-diffusive regime. Iida (2016) reported a super-diffusion at scales smaller than 10\(^{3.8}\) km and sub-diffusion on larger ones.

In present work, we apply a random walk model to the proper motions of CBPs to estimate the diffusion coefficient.

2. Data and Reduction Method

For the application of the random walk model, we used position measurements of CBPs from the images taken by Atmospheric Imaging Assembly instrument on-board Solar Dynamics Observatory (AIA/SDO; Lemen et al. 2012). The data set covers a period of more than 5 months (2011 Jan. 1 – 2011 May 19) with a cadence of 10 minutes. First, a segmentation algorithm was used to identify and track CBPs in subsequent images (a modification of algorithm by Martens et al. 2012) and then the data were filtered for outliers, height corrected and finally, residual rotation (\( \Delta v_{rot} \)) and meridional (\( v_{mer} \)) velocities were calculated (Sudar et al., 2016).

The same data set was already used to analyze meridional motions and Reynolds stresses by Sudar et al. (2016), while similar CBP measurements covering only two days were used to derive differential rotation profile of the Sun (Brajša et al., 2014; Sudar et al., 2015) and calculate diffusion coefficient (Brajša et al., 2015). In this paper, we repeat the analysis of Brajša et al. (2015) on a larger 5-month data set.

Within the random walk model, where CBPs are viewed as "particles" that diffuse into the surrounding medium, diffusion coefficient is calculated as:

\[
D = \frac{\langle l^2 \rangle}{4\tau},
\]
where \( l \) is the mean free path, i.e. the distance traveled by CBP during its lifetime \( \tau \). The mean free path was calculated for each CBP as:

\[
l = \frac{\Delta}{\tau},
\]

where the absolute velocity (\( v_{\text{abs}} \)) was determined using:

\[
v_{\text{abs}} = \sqrt{\Delta^2 v_{\text{rot}}^2 + v_{\text{mer}}^2}.
\]

3. Results and Discussion

Figure 1 shows the distribution of \( v_{\text{abs}} \) for the entire data set. Most CBPs have velocities in the range 100–300 m s\(^{-1}\), in line with Brajša et al. (2015), but somewhat larger than measured by Brajša et al. (2008) on SOHO/EIT images.

Lifetimes of CBPs can be seen in Figure 2 (note the logarithmic ordinate axis). There is an exponential decay in number of CBPs with longer lifetimes which is also observed in other studies (e.g. McIntosh and Gurman 2005).
The least squares fit gives a typical decay time of 3.2 hours, a value close to the mean value of CBP lifetime of 3.7 hours (see Table I). The lifetime histogram is sharply limited on both sides, at 1.5 hours because only CBPs that were visible on 10 or more subsequent images were used, and at 24 hours because the used algorithm tracked CBPs over one day and then resets for the next day, treating the same long living CBP as two independent ones. This fact also explains the bump in the tail of the lifetime distribution.

**Table I:** Average values of lifetime ($\tau$), absolute velocity ($v_{abs}$), mean free path ($l$) and diffusion constant ($D$) for the complete data set and several subsets of lifetime.

<table>
<thead>
<tr>
<th>Subset</th>
<th>$N$</th>
<th>$\bar{\tau}$ [h]</th>
<th>$\bar{v}_{abs}$ [m s$^{-1}$]</th>
<th>$\bar{l}$ [km]</th>
<th>$\bar{D}$ [km$^2$ s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; \tau \leq 6$ h</td>
<td>69603</td>
<td>2.78</td>
<td>298</td>
<td>2700</td>
<td>263</td>
</tr>
<tr>
<td>$6 &lt; \tau \leq 12$ h</td>
<td>9475</td>
<td>8.13</td>
<td>140</td>
<td>4020</td>
<td>193</td>
</tr>
<tr>
<td>$12 &lt; \tau \leq 18$ h</td>
<td>1551</td>
<td>14.35</td>
<td>100</td>
<td>5110</td>
<td>167</td>
</tr>
<tr>
<td>$18 &lt; \tau \leq 24$ h</td>
<td>337</td>
<td>21.05</td>
<td>81</td>
<td>6160</td>
<td>170</td>
</tr>
<tr>
<td>all</td>
<td>80966</td>
<td>3.70</td>
<td>275</td>
<td>2910</td>
<td>235</td>
</tr>
</tbody>
</table>

The results are presented in Table I, for all data points and over several subsets of various lifetime. The mean free path is $\approx$3000 km with values...
increasing to 6000 km for the longer living CBPs. The opposite trend is seen in absolute velocity with values going from 300 m s$^{-1}$ down to 100 m s$^{-1}$. Finally, the mean diffusion coefficient is 235 km$^2$ s$^{-1}$ with a somewhat larger value for short living CBPs, but settling to $\approx$170 km$^2$ s$^{-1}$ for the longer living ones.

Measured values of diffusion coefficient are lower than required by simulations (600 $\pm$ 200 km$^2$ s$^{-1}$, Wang et al. 1989) but very similar to other results obtained by tracking CBPs (Brajša et al., 2008, 2015), magnetic concentrations (Mosher, 1977; Hagenaar et al., 1999) and magnetic bright points in G-band images (Berger et al., 1998; Utz et al., 2010). The variation of $D$ with lifetime suggests a sub-diffusive regime, also found by Lawrence and Schrijver (1993), but in contrast with super-diffusive results of Abramenko et al. (2011). Iida (2016) found that super-diffusion changes to sub-diffusion at $10^{3.8}$ km, roughly corresponding to the mean free path of longer living CBPs in our data set, which could explain the difference between various observations.

4. Conclusion

In this work, we used motions of CBPs to estimate diffusion coefficient. While some part of the observed motions can be due to magnetic reconnection processes associated with CBPs, the main part should come from the underlying motions of solar plasma because the overall velocity field measured from CBPs corresponds well to those derived from Doppler measurements (Sudar et al., 2016). The motions of CBPs suggest a diffusion coefficient of 170–270 km$^2$ s$^{-1}$ with a possible sub-diffusive regime on longer timescales. In further work, we plan to analyze this anomalous diffusive behavior in more detail.

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